International
Fertilizer Industry
Association

IFA Technical Conference

Amman, Jordan

2-6 October 1994

AUTOMATION OF THE MINING PROCESS IN SASKATCHEWAN POTASH MINES

G.W. Moore, S.J. Fortney and J.L. Lewis
Potash Corporation of Saskatchewan Inc., Canada

RESUME

Potash Corporation of Saskatchewan continue à consacrer des ressources à l'automatisation du processus d'extraction dans ses opérations souterraines. La combinaison de projets d'automatisation du matériel avec des systèmes de communication de plus en plus sophistiqués dans les mines augmente régulièrement la productivité tout en diminuant les coûts de production.

Notre objectif pour l'an 2000 est d'avoir la possibilité de commander et de contrôler à distance le matériel d'extraction au moyen duquel un distributeur en surface pourrait commander toutes les unités de production avec un groupe mobile d'opérateurs au fond pour régler ou entretenir les appareils. Cet objectif est tout à fait à notre portée.

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INTRODUCTION

Potash Corporation of Saskatchewan Inc. (PCS) owns and operates five potash mining and processing facilities in Saskatchewan, Canada along with an additional mine, mill and port facility located in New Brunswick, Canada. The productive capacity of the PCS owned and operated mines combined with a long-term mining and processing agreement with International Minerals and Chemical Corporation (Canada) Ltd. is 11 million tonnes per year. PCS represents 13 percent of world potash production, 20 percent of world capacity, and controls 40 percent of the world's excess capacity.

At four of the Saskatchewan operations of PCS, potash is extracted by underground room and pillar mining methods using large continuous boring machines. The fifth Saskatchewan operation utilizes solution mining technology while the New Brunswick mine employs a mechanized cut and fill method.

In order to improve the productivity and occupational environment of its mining operations, PCS has focused considerable effort in the area of Research and Development aimed at automation of both the mine and mill processes. Efforts to automate the mining process have been on-going since 1983, and in October, 1989, complete automatic mining machine control was achieved for the first time at Rocanville Division. This paper focuses on the Rocanville development and will discuss additional on-going automation projects.

BORER AUTOMATION

Rocanville Division

Mining Method

At PCS Inc., Rocanville Division, mining takes place at a depth of 960 m in a 2.44 m thick potash deposit known as the Esterhazy member of the Prairie Evaporite formation. The vast majority of ore is extracted from the mine using continuous mining machines and conveyor belt haulage systems. Development entries and mining rooms usually 1 525 m long are driven using extensible conveyor systems. Production mining takes place in long parallel rooms within pre-developed panels. The typical panel layout is shown in **Figure 1**.

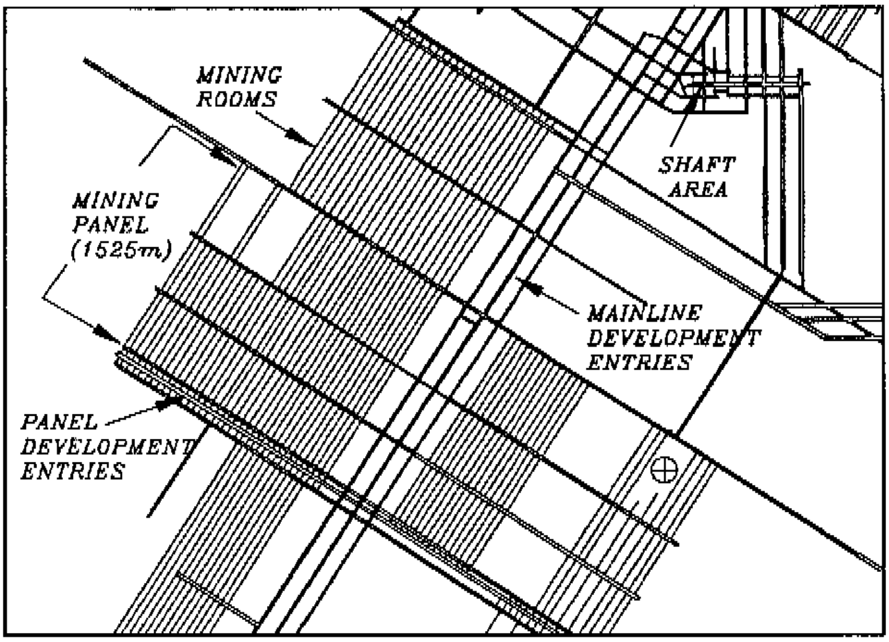

FIGURE 1: Rocanville South Mine

Mining rooms are excavated in three passes to produce a 20 m wide opening. The initial full face excavation that opens virgin ground is referred to as first pass. During first pass cutting, a 1060 mm extensible conveyor belt extends continuously with the mining machine as the face advances. Conveyor support hardware is installed at 3 m intervals. Belting is added to the extensible storage unit after each 61 m of advance. Once the first pass of a mining room is completed, the conveyor is anchored in place with a stationary tail pulley. The completed first pass entry is 7.9 m wide and usually 1.5 km long with the extensible conveyor floor mounted on centerline.

As shown in **Figure 2**, second pass mining consists of widening the room to 14 m. A cross conveyor transfers the excavated ore to the first pass extensible conveyor continuously as the face advances. Upon completion of second pass, the borer turns and slashes a third pass from the opposite rib. Third pass mining is similar to second pass in that the room is widened an additional 6 m while transferring ore to the extensible conveyor.

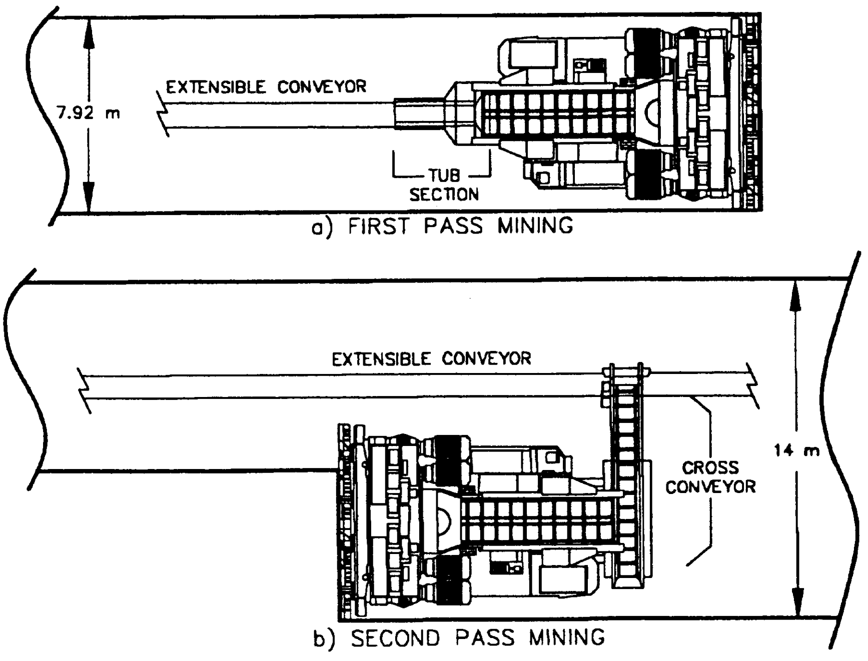

FIGURE 2: Mining Sequence

Mining Machine

The mining machines employed at PCS Inc., Rocanville Division are Marietta 780-AW4 continuous borers **(see Figure 3)**. These 236 tonne machines are capable of cutting a 7.92 m wide by 2.44 m high potash face at a rate of 0.46 m/minute (1 000 tonnes/hour). Four 298 kW A.C. motors geared to four rotary cutting heads provide the principle cutting capability. Two 39 kW D.C. tram motors each powering track crawlers produce the motive force.

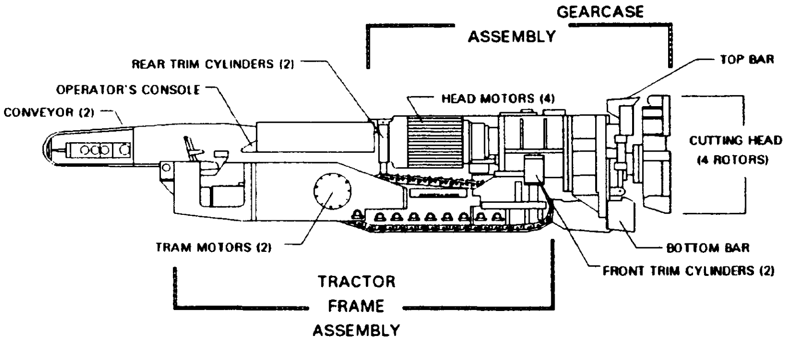

FIGURE 3: Marietta 780-AW4 Continuous Borer

The mining machine is composed of two primary sections. The tractor frame section consists of the crawlers and D.C. drive assemblies mounted to a frame that supports the remainder of the mining machine. The gearcase section, consisting of the main gearbox, cutting head, and conveyor assembly, rests atop the tractor frame on 4 hydraulic trim cylinders. Trim cylinder activation positions the gearcase section independently from the tractor frame. The left and right front trim cylinders are located on opposite sides of the machine directly behind the cutting head. These two cylinders operate independently to control lateral roll. Two rear trim cylinders operate in tandem and are located at the rear of the gearcase near the midpoint of the tractor frame. The extension of the front trim cylinders with respect to the rear trim cylinders controls the machine's vertical pitch.

Control Functions

The vertical direction of mining is dictated by the pitch of the gearcase. Gearcase pitch establishes the elevation of floor being cut ahead of the tracks. If the machine is to go up, gearcase pitch is increased to cut floor above the track elevation. The reverse is true for steering the machine down. Adjusting the gearcase pitch is accomplished primarily by extending or retracting the right and left trim cylinders. This must be done in tandem to maintain laterally level cutting (zero roll).

During first pass mining, the operator steers the machine up or down depending on the vertical position of the ore zone. A visual "marker seam" exists in the ore that the operator follows to achieve the desired elevation and best ore grade. The vertical position of first pass establishes the ore grade quality extracted from the entire room.

Lateral navigation in first pass is accomplished with the aid of a visible laser beam aligned with the azimuth of the entry. The operator steers the machine left or right to maintain the laser beam within a fixed target area located on the machine's top cutting bar.

Second and third pass navigation consists of following the profile of the first pass entry. In order to create a laterally smooth back, the operator must maintain a consistent face width while following the roof elevation of first pass.

System Design

Automation is achieved when the mining machine can follow a set course through the ore zone and mine at a pre-determined rate without operator intervention.

The automatic controls developed for the mining machine may be described as an "automatic pilot" system. Once the machine is up and cutting at conditions acceptable to the operator, triaxial guidance and advance rate control duties may be completely turned over to an on-board microprocessor.

There are five modes of machine control selectable by the operator: manual, semi-automatic, first automatic, second automatic, and third automatic. The manual mode disables all automatic control intervention from the microprocessor. Semi-automatic causes the microprocessor to maintain operator selected cutting amperage. First automatic enables complete automatic control in first pass involving ore grade analysis, laser guidance, cutting amperage maintenance and tub control. Second and third automatic allows complete automatic control in second and third pass involving first pass location, cutting amperage maintenance, and cross conveyor positioning.

The automatic control system was designed for reliable operation in a harsh underground mining environment. Readily available industrial components were used wherever possible. Sensors have been kept to a minimum and protectively integrated with the rest of the mining machine. All machine controls and sensor locations are wired to feed the on-board microprocessor. Considerable effort was made not to alienate the operator with new control arrangements. **Figure 4** shows the control system arrangement.

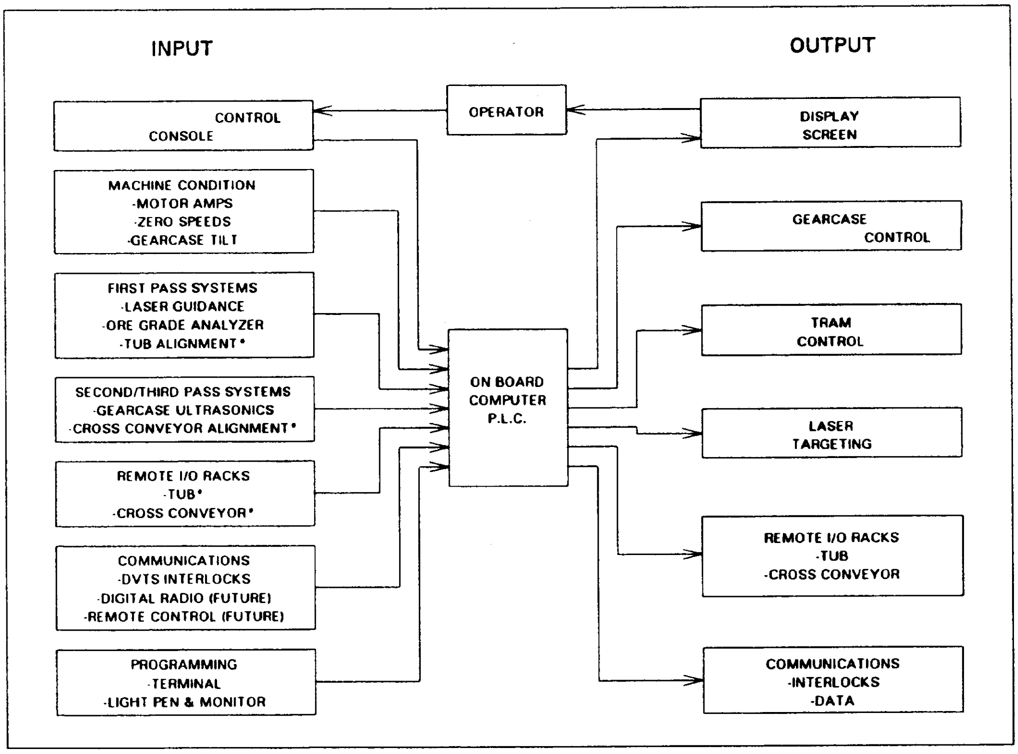

FIGURE 4: Automatic Control System Schematic

Sensory Feedback

There are six primary sub-systems that provide condition feedback to the microprocessor. The ore grade analyzer, laser guidance, first pass profiling, and cross conveyor alignment systems monitor external mining conditions. Their location on the mining machine is shown in **Figure 5**. Motor current, inclinometer, and other sensors which monitor machine condition are located internally in the machine's wiring or enclosures.

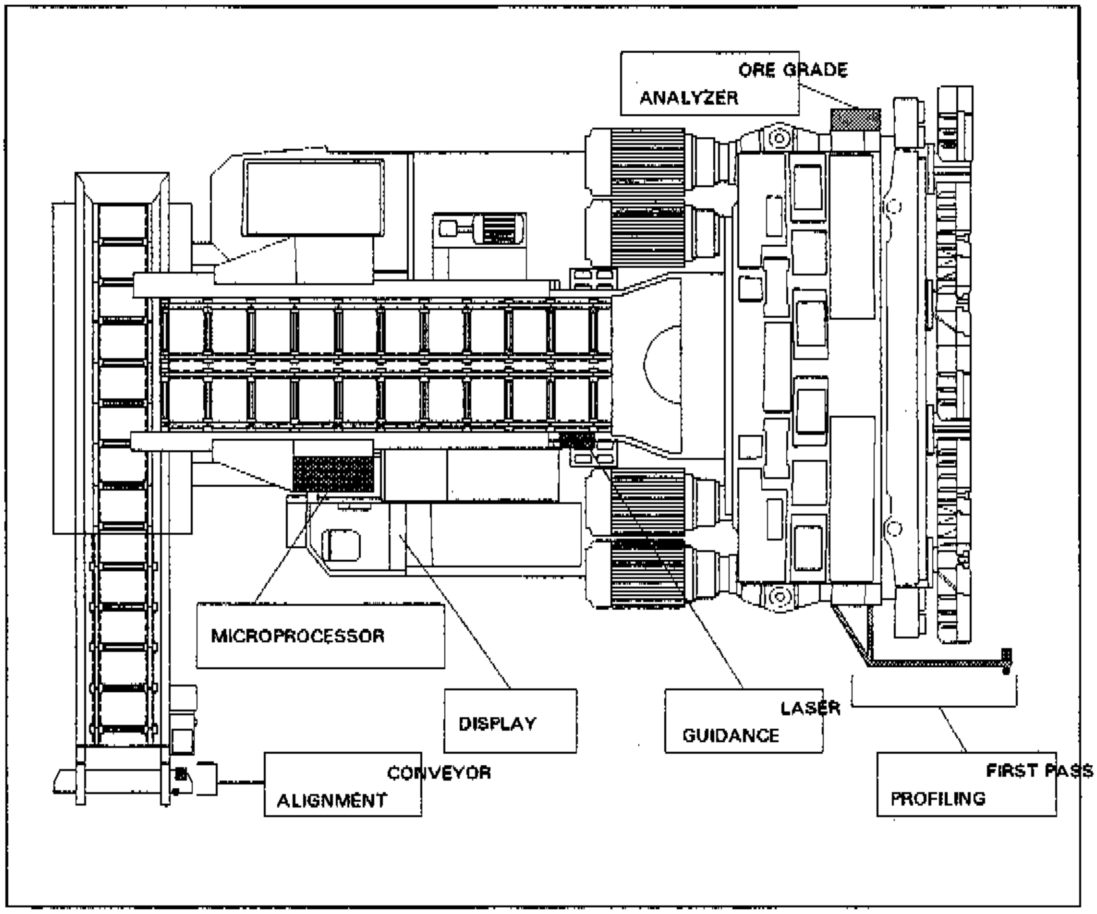

FIGURE 5: External Sensor Locations

Ore Grade Analyzer

The ore grade analyzer is used to guide the mining machine vertically in first pass by locating the position of highest recoverable ore grade. Based on readings from the device, the machine is steered up or down manually by the operator, or automatically by the microprocessor.

The principle behind the analyzer is the scintillation detection of gamma emissions from the potassium-40 isotope found in the ore. Seven teledyne S-88-I gamma detectors consisting of sodium iodide crystals, photomultipliers, and amplifiers are mounted inside a 227 kg lead shielded enclosure.

Each gamma detector is encased in at least 5.1 cm of lead in a manner that allows gamma emissions to contact the detector only through directed windows. The window geometry is such that each detector receives emissions from a specific section of rock. Since the number of radiometric counts detected per unit time is directly related to potash concentration, the sensor provides a segmented profile of roof, wall, and floor ore grades **(see Figure 6)**.

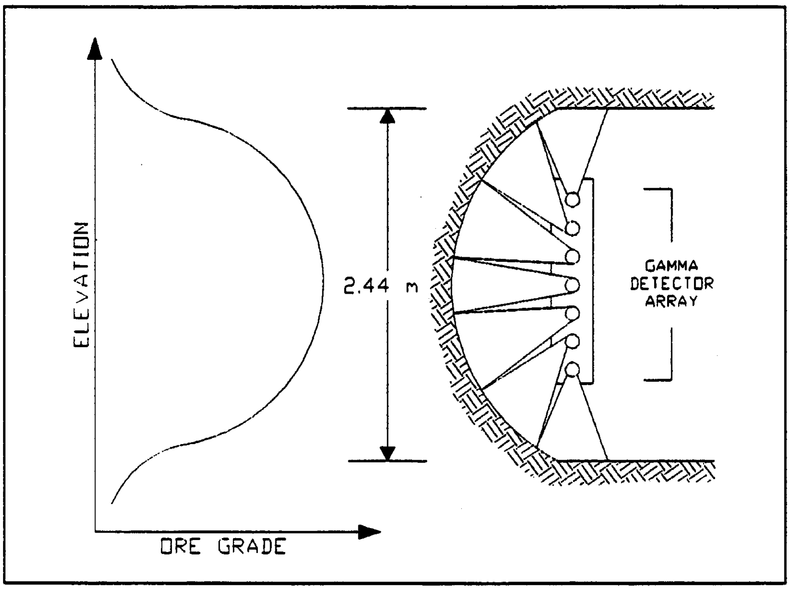

FIGURE 6: Ore Grade Analyzer Principle

The sensor head is mounted to the mining machine on the left hand side of the gearcase directly behind the cutting head. Detector information is received by the microprocessor where it is time counted. A histogram representing a weighted average of ore grades over the last 5 minutes of cutting is updated on the display screen every 30 seconds. If the histogram is skewed towards the roof, the mining machine is too low. If it is skewed towards the floor, the machine is too high. During both manual and automatic operation, the machine is steered vertically to achieve a normal distribution indicative of optimum ore recovery. Examples of the display profiles are given in **Figure 7**.

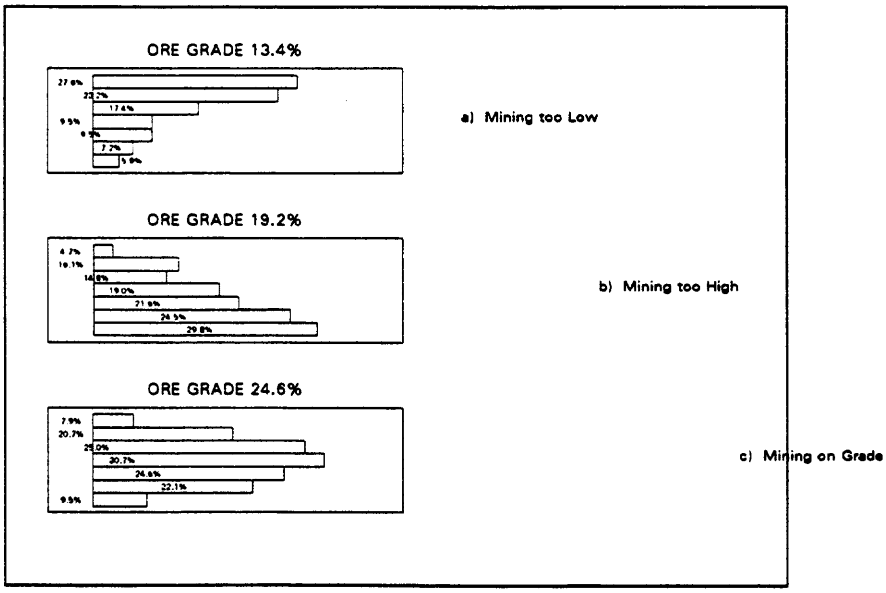

FIGURE 7: Ore Grade Profiles

Laser Guidance

During first pass mining, a visible laser modified for automatic vertical targeting is used to keep the entry on a desired heading. Automatic targeting is accomplished using a modified grade laser capable of changing the beam's vertical position based on control signals received from the microprocessor.

The laser assembly is mounted to the roof of first pass behind the mining machine with the beam aligned to the desired azimuth of the entry. Laser power and control signals are provided via a 213.4 m long shielded cabled reeled at the mining machine. The laser beam points forward intersecting a reflective target located on the machines top bar.

An artificial vision module and camera assembly is used to detect the position of the beam within the target area. A filter allows only the specific light produced by a red HeNe laser to be detected by the camera. The camera assembly is housed inside a dust proof enclosure mounted to the back side of the gearcase near the rear trim cylinders.

Video signals from the camera assembly are fed to the microprocessors vision input module. The digitized image is analyzed using a grid of pre-programmed rulers in the field of view. The passing of the image over these rulers locates beam position both vertically and horizontally to within 1.52 mm. During automatic operation, appropriate tram outputs are activated to maintain the laser in the center of the grid.

Ultrasonic Guidance

During second and third pass cutting, two ultrasonic transducers are used to follow the profile of the first pass entry. These devices measure the distance to the first pass rib and roof by timing the reflection of sonic waves. Each transducer consists of a sensor head cabled to a signal processor. Both the lateral and vertical sensor heads are mounted to the mining machine on a removable arm that projects out in front of the right outside rotor. Distances to the rib and roof are, therefore, measured immediately ahead of cutting. Measurement accuracy is 2.54 mm over a 1 to 7.62 m range. Readings from the lateral sensor dictate the tram power differential required to maintain a set wall cutting depth. Signals from the vertical transducer dictate the right trim cylinder extension or retraction necessary to match the roof of first pass.

Gearcase Attitude

Two Servo inclinometers are used to monitor the pitch and roll angle of the mining machine's gearcase. Both inclinometers are housed inside the ore grade analyzer sensing box.

Motor Current

The amperage drawn by the four 298 kW head motors gives an indication of cutting force being applied to the face. Head amperage levels are dependent on the amount of power supplied to the tram motors under varying bit wear and ore hardness conditions. The current drawn by the four head motors and both tram motors are continuously monitored by current transducers mounted to the motor power feed cables. Current transducers are also used to monitor pump motor and conveyor motor amperage levels.

Conveyor Alignment

When cutting second and third pass, a cross conveyor transfers the ore from the mining machine to the extensible conveyor belt. The cross conveyor is arranged such that the top extensible belt runs through the discharge chute on troughing idlers. The chute must, therefore, be positioned directly above the extensible belt centerline and trained in the direction of the belt travel.

Automatic cross conveyor alignment involves continuously monitoring the location of the extensible belt in the chute and the proximity of the chute from the mine roof. A line scan camera fitted with a wide angle lens is used to measure the position of the extensible belt. Two programmable rulers within the camera's field of view locate the belt edges to within .13 mm. A microprocessor program adjusts the chute training and extension cylinders to maintain the belt within 5.1 cm of centerline.

The distance from the top of the chute to the mine roof is measured with an ultrasonic transducer. The desired height of the discharge chute above the extensible conveyor is automatically maintained to within 50.8 mm.

Machine Condition

A variety of other feedback elements needed to monitor adverse machine conditions have also been incorporated into the automatic control system. These inputs provide automatic tram or hydraulic pump shutdown and diagnostic alarms on the display.

Extensible conveyor conditions such as belt running, belt ahead, and belt storage limits are continuously monitored. Contact switches monitor machine/roof collision and excessive gearcase tilt. Amperage overload is monitored for every electrical motor on the mining machine. Temperature detectors monitor excessive temperatures in the tram motors and the microprocessor enclosure. Zero speed switches monitor both the trim chain and conveyor chain operations.

Microprocessing

On-board microprocessing is performed by an Allen-Bradley PLC 5/30 industrial processor having 32 K RAM. Aside from the vision input required for laser guidance, the automation program contains 100 timers, 10 PID loops, 28 analogue inputs and 250 discrete I/O.

Environmental Considerations

The environment at the mining machine presents several problems for electronic equipment.

The problems of dust, physical damage, oil spills and lack of space were handled by placing all electronic components in a sealed steel box. The box joints were all continuously welded so there were no leaks. Wherever cables entered the box, water tight connectors were utilized. Any lids or accesses to the box were machined to provide a dust tight seal.

To address the heating problems, a thermoelectric cooling system was employed. The cooling system consists of two units of four solid state thermoelectronic cooling wafers sandwiched between two heat sinks.

The problems with the high electrical noise and poor voltage control were dealt with by using isolating transformers which only supply the electronics. Whenever possible, the cables were routed away from areas of high electrical noise and the cable lengths were kept as short as possible. In all cases, shielded and double shielded cables were utilized.

The vibration problems on the miner were primarily dealt with by using industrial grade components which could withstand vibration.

Benefits

1. Benefits resulting from mining machine automation at Rocanville Division began in December 1988 when number 50706 machine left the overhaul shop after being fitted with the first mining machine automation package. Since that time, this machine has mined over 5 million tonnes of potash ore under automatic control and has exceeded the conventional limit for overhauling the gearcase by over two million tonnes. Gearcase overhauls on mining machines cost an average of $350,000 and takes the mining unit out of production for periods of up to three months.

2. In March, 1993, the last of the five 230 tonne mining machines at Rocanville was converted to automatic control. Altogether in 1993, more than three million metric tonnes of potash ore was mined operating in the automatic mode. Over 160 000 metric tonnes of this ore was mined without any operating personnel being present at the mining machine. The ability to leave the mining machines operate unattended has improved the productivity of the mining faces while leaving the operators free to perform other work. Machines have also been operated in the absence of operators during lunch period and during shift changes thereby improving continuous ore supply to the refinery. Refinery delays attributed to a shortage of raw ore have been reduced by 80% over previous years.

3. A daily production record was set on March 25, 1994, when number 50705 mining machine operated for over 17 hours on automatic control, including through shift change, producing a record 14 200 tonnes of potash ore. This tonnage represents 70% of the potash ore necessary to sustain refinery operations for a day.

4. An ore analyzer mounted to the front of the mining machine is the part of the automation package that guides the machine through the orebody based on the position of the best ore. The recovery of available ore grade in the mine is now averaging over 96% which translates into a mill feed quality improvement of 0.5% K_2O. Using 1994 budget figures, this represents the ability to produce 26 500 tonnes of additional product annually without additional cost.

5. Over the last three years automatic control of the mining machines has become more common and more widely accepted by operating personnel. While mining machine automation has not changed the physical environment at the mining face, the diversity of control and new mobility afforded to operating personnel has greatly improved working conditions. This is reflected in the fact that in 1993, the amount of time that the mining machines were utilized for actual mining operations increased by 16% over previous years.

6. The constant power and steering adjustments necessary to operate the mining machines are now managed by on-board computers. This not only relieves operator fatigue but also provides a consistency in mining machine control that reduces electrical and mechanical fatigues as well. Over the last three years, the cost of maintenance performed on the mining machines per tonne of ore mined has dropped by 30% representing an annual saving of $400,000. Over the last two years, mechanical and electrical availability of the mining machines also improved to 85%.

7. The ability to run the mining machines unattended through lunch and through shift change has levelled mine production such that there is less need to operate more than three mining machines at one time. The net effect has been an average peak power (electrical demand) reduction of 1 500 kV.A per month or a $15,000 savings per month.

Saskatoon Area Mines

Mining Method

At the Saskatoon area operations of PCS, mining takes place at a depth of about 1 000 m and the ore zones being mined vary in thickness between 3.35 m and 5.18 m. One geological feature inherent to all of the Saskatoon area mines that is not found in the Rocanville ore body is the presence of numerous clay bands **(Figure 8)**. These clay partings are zones of weakness that caused severe ground control problems during the early days of mining in the area. The problems were finally overcome by cutting the mine entries to a predetermined clay marker band combined with the development of an innovative mining method called stress relief mining **(Figure 9)**. This method combines a cutting sequence whereby outside entries are cut first to relieve the stress on the protected inner entries along with internal yield pillars that allow the system to close in a controlled fashion. All of the mines which operate in the upper ore zone in the Saskatoon region utilize a form of stress relief mining. The Lanigan mine which operates the lower "B" zone does not employ stress relief mining but nonetheless has to cut to a predetermined clay band.

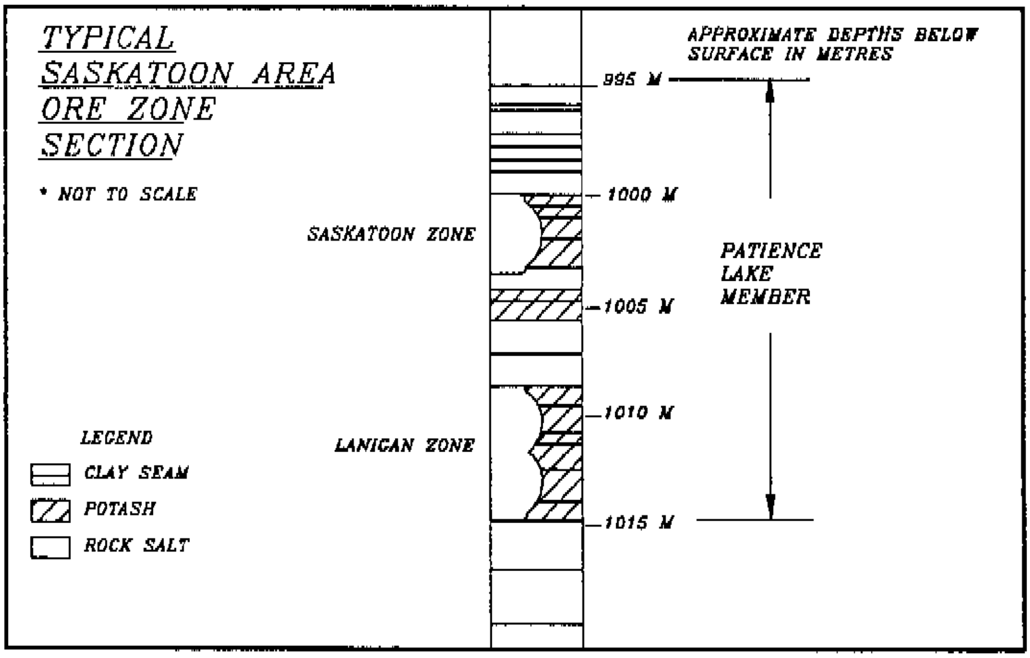

FIGURE 8: Saskatoon Ore Profile

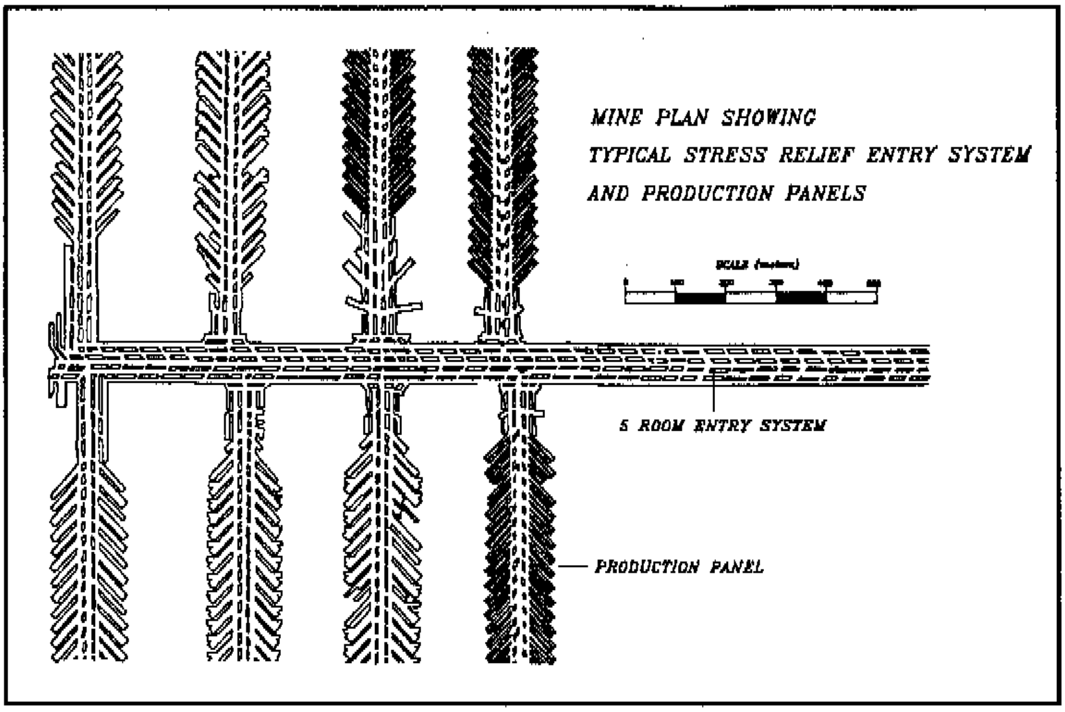

FIGURE 9: Stress Relief Mining

System Design

Because of the different geological conditions in the Saskatoon area mines that requires the borers to cut to a predetermined clay band, an alternate system to the Rocanville ore grade analyzer had to be developed to provide the vertical navigation requirements. What was required was a means of discriminating and tracking the clay seams. Several techniques were evaluated during the early to late eighties with varying degrees of success. Efforts focused on trying to determine a single discrete physical property by which the clay seam could be identified and discriminated from the surrounding ore. Properties investigated and evaluated included resistivity, conductivity, capacitance, hardness and fluorescence. Each evaluation met with little or limited success. As the operators use their sense of vision to follow the clay seam, the project leader proposed to develop a visual tracking unit.

An evaluation of the optical properties of the ore and clay seams was undertaken to identify any inherent properties which could be used. One such property was identified in late 1990. Using proprietary techniques, this property was exploited and it became apparent that the clay seam could be discriminated.

Once a suitable image was obtained a search was begun to determine the best means of processing this image. Various vision based systems were field tested during 1991 and 1992. By mid 1992, a system which met our requirements and was compatible with our existing Programable Logic Controllers was found.

Originally developed for use by the U.S. Military, the system chosen allowed automatic tracking of a multi-dimensional target. Environmental problems such as heat, dust and vibration were overcome and a workable system was field tested in 1993.

Once the clay seam could be clearly identified and tracked, its target's position could be read into an on-board processor and the borer's position could be referenced to the orebody. Trending software was used to compensate for local fluctuations in the seam. PLC's could now be used to control the borer's position in the orebody.

By incorporating PCS's proprietary laser guidance, tram control and clay seam tracker systems, the borer's position and advance rate can be monitored and maintained by an on-board PLC. By late 1993, the capability of full automation had been demonstrated over many trial runs.

Future Work

During the remainder of 1994, field work will continue to complete debugging of the complete system at our Cory operation. Additional work is required on the trending software and the utilization of additional cameras will be tested to ensure that the clay seam is tracked on both the left and right hand side of the borer. Continued fine tuning of the trending software is also ongoing to eliminate false readings caused by erratic seams. Necessary diagnostic controls will also be mounted to ensure automatic shutdown of the borer should problems occur.

Engineering personnel continue to evaluate alternate vision based systems that have features which may better meet our needs. It is anticipated that a packaged system will be available for installation on production borers in the Saskatoon mines by the end of 1994.

BRIDGE AUTOMATION

In order to fully automate the mining process at the Allan and Cory mines of PCS, it is essential that the mobile bridge conveyors used behind the borers are also automated. In order to cut the stress relief development and production panels, both mines employ multi-section mobile bridge conveyors. The bridge conveyors consist of either five or seven wheel mounted "piggy backing" mobile conveyor units **(Figure 10)**. The lead bridge is coupled to the borer such that when the borer advances the bridges follow, these bridges have an extended length of 90 m. During extension the tail section of the bridge conveyor remains positioned over a floor mounted room conveyor. Ore received at the head section is conveyed and cascaded from bridge to bridge and ultimately discharges via a chute onto the room conveyor which is straddled by the last bridge section.

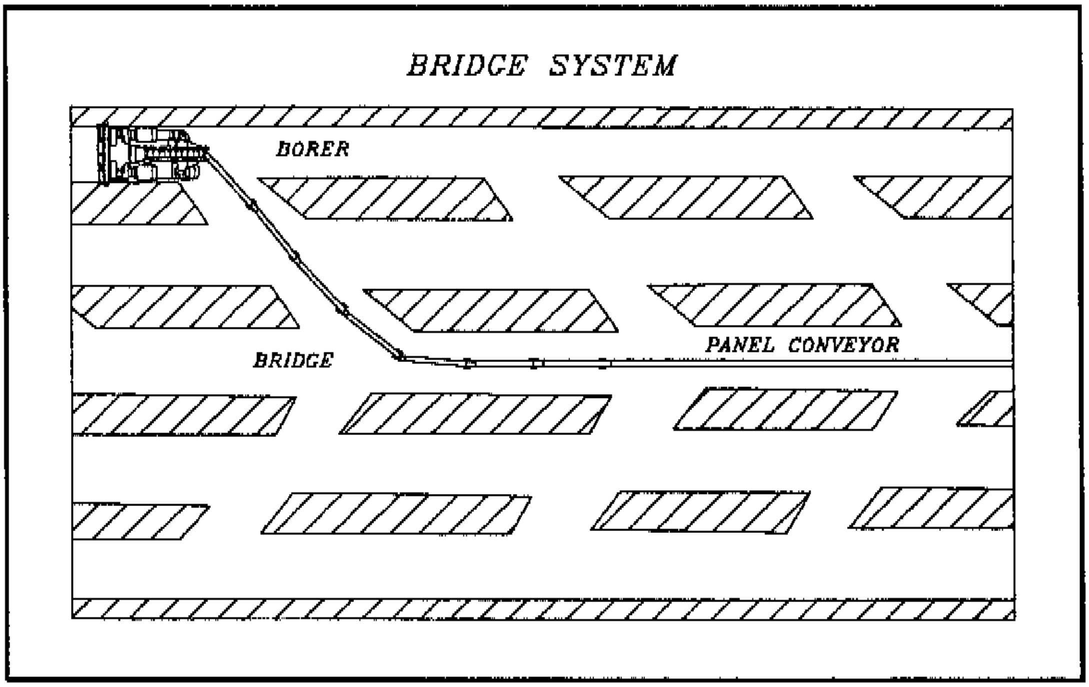

FIGURE 10: Bridge System

At present, operators maintain bridge position behind the boring machine using either manual tram or radio remote controls. The controls activate wheel motion and tram direction. The operator maintains visual contact with the equipment and ensures that the bridge conveyors do not impact walls, equipment or people. The operator is responsible for maneuvering corners both during borer advance and retreat. An operator at the tail section maintains chute alignment over the room conveyor to minimize spillage.

System Design

The scope of the project was to design and install an autonomous control system which would enable the bridge conveyor to track into a mine heading under its own guidance, advance with the borer, and retreat. Although the intent is to fully automate bridge advance and retreat, manual operation will remain optional.

Under the system design each section of the bridge conveyor is treated as an independent vehicle that must follow the next one to within pre-specified tolerances. The bridge conveyors therefore advance and retreat based on their sensor feedback and the pre-defined rules. Each bridge unit is equipped with an array of sensor types including analog proximity sensors, ultrasonic sensors, potentiometers and proximity limit switches that monitor the various functions. Each bridge unit is equipped with a hardware module that collects sensor data and transmits it to embedded PLC's that control bridge motion. It is planned that the installed sensors and embedded PLC's will perform all functions currently performed by two operators.

Progress to Date

Necessary control hardware and sensors have been installed on the test five section bridge conveyor. Field testing was initiated and on-going modifications to the control logic are underway. Integration of the sensors, hardware and software and debugging of the system under operating field conditions is underway. The project is scheduled for completion and evaluation during the last half of 1994.

Potential Benefits

Initially, an automated bridge unit will reduce operator exposure to noise, heat, dust and moving equipment. In the near term, automation of the bridge and borer units could result in the elimination of two operators per mining unit per shift at our Cory and Allan operations.